Dynamic Range Issues for Magnets & Machines

- Existing Machines
- Basic Issues
- Injection Energy Scaling
- Design Issues (or how bad can you get and still work ?)
- Solutions
  - Better Magnets
  - Better Machines
- So what is the (correct) dynamic range for a 50 Tev Ring ?

Existing Machines

- Definitions:
  - Machine: ratio between operating/injection energy
  - (Magnets: ratio between highest/lowest field within specs)
- Examples

– Tevatron	7:1	fields	0.66T-> 4.5T
– RHIC	9:1	fields	0.39T-> 3.45
– HERA	20:1	fields	0.23T -> 4.5T (5.5T)
– LHC	16:1	fields	0.54T -> 8.4T

(n.b. AGS Booster 95:1 Main Ring 60:1)

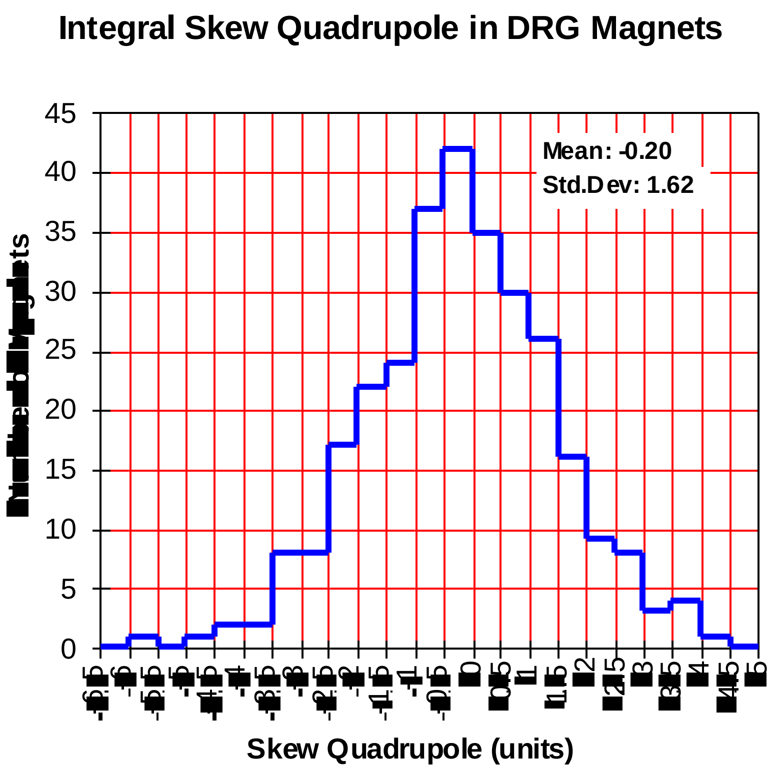
Differences at the factor of ~3 level. Most choices heavily influenced by existing injector

- General assumption is that more dynamic range is good

Basic Issues

For a given machine design

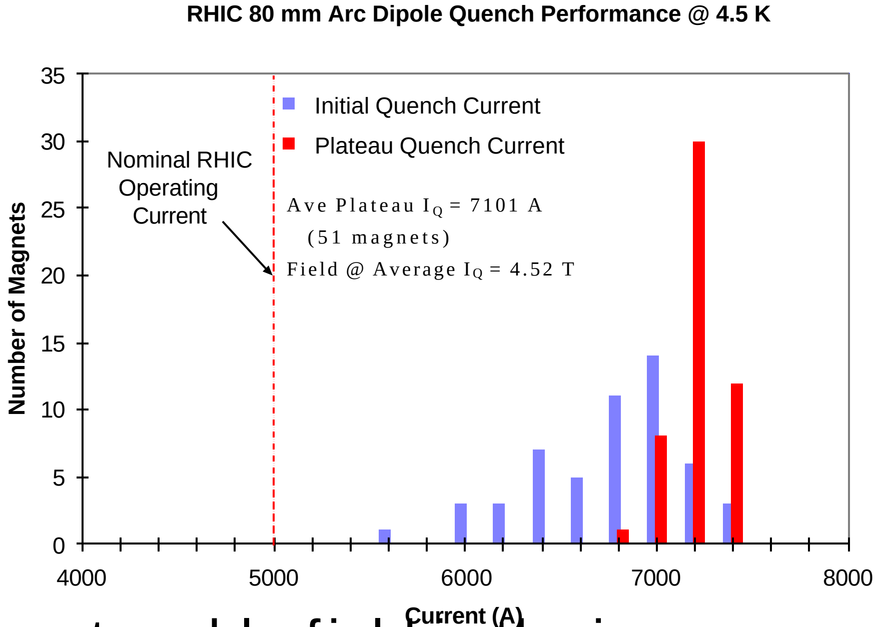
- Injection energy set by lowest usable field level which is, in turn, set by field quality distribution



Effective field quality distribution is determined by geometric field + dynamic effects: persistent currents & eddy currents -> snapback, ramp rate dependance etc…. These effects have systematic/allowed & random/ non-allowed harmonics. Ends v's bodies etc..

Basic Issues cont.

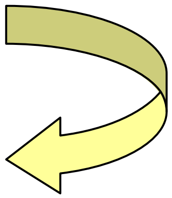
Operating energy determined by quench current distribution



Generally the definition of lowest usable field is the issue which poses the interesting accelerator design questions. Quench characteristics determined by magnet technology, tends to be less flexible.

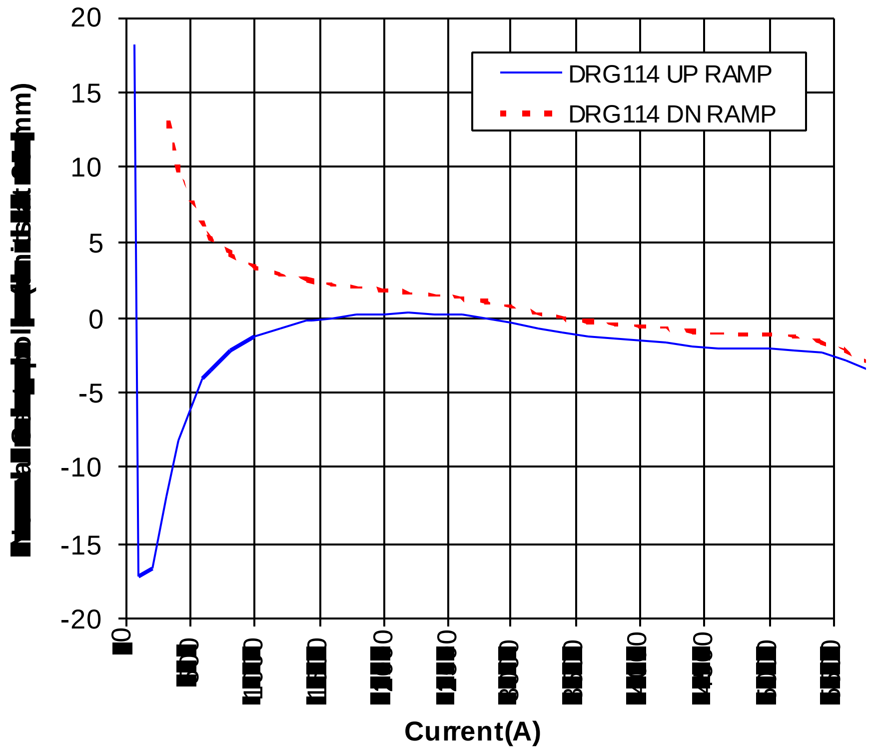
Machine sets injection energy

Magnets set top energy



Injection Energy Scaling

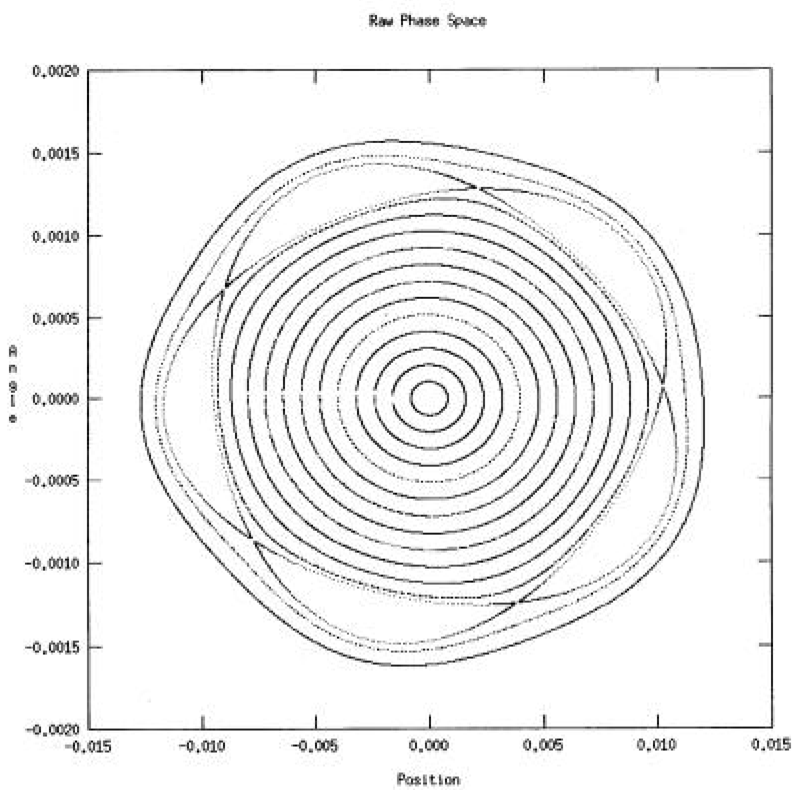
- Magnetic field quality gets worse with decreasing excitation: persistent currents
- Some machine parameters get worse with decreasing energy i.e. beam size. Aperture defined in terms of beam sigma
- Instabilities generally worse with decreasing energy α 1/Bρ
- Some machine parameters get better with decreasing energy i.e. injection lattice. Relaxing focussing at injection can remove the IR magnets from consideration (less sensitivity).

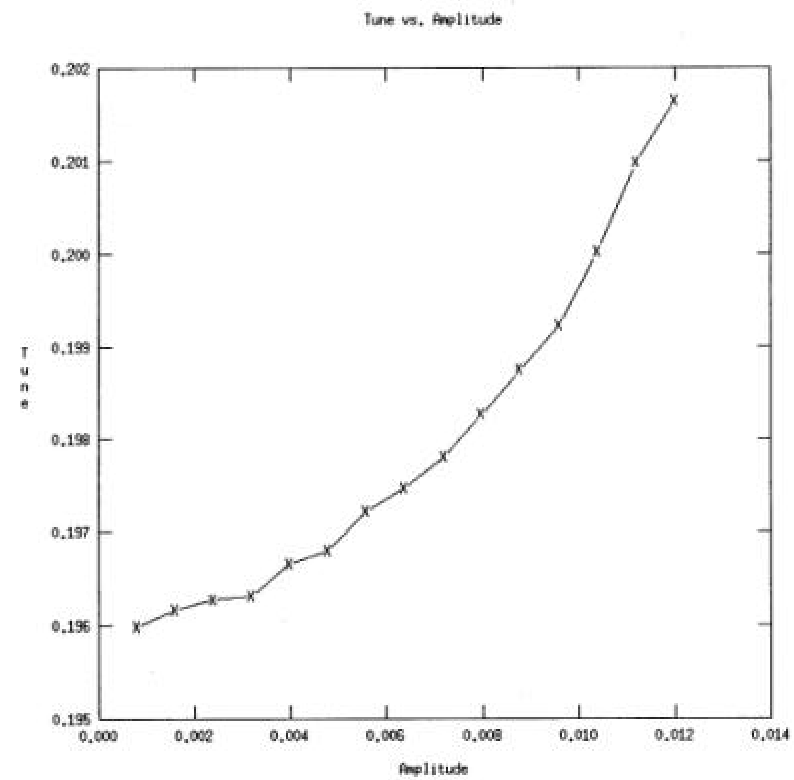


This results in dynamic range defined by the arc magnets

Design Issues (or How bad can you get and still work ??)

- Linear aperture, non-linear aperture, dynamic aperture





RHIC at injection

Design Issues (or How bad can you get and still work ??)

Tracking predictions v's machine measurements

SPS with tune modulation

HERA at injection

Tracking results in qualitative agreement (70%) of calculated

Design Issues (or How bad can you get and still work ??)

- Operating Conditions
  - Dwell time -> injection lifetime
  - Beam tolerances -> emittance growth (non-linear aperture), beam loss sensitivity (dynamic/physical aperture)

- Aperture requirements
  - This issue gets more complicated as the injection energy increases and the beam size gets smaller

  Aperture = constant + n sigma (n = ~7-8)

  - If sigma = 2mm then this is easy, if sigma = 0.1mm ??

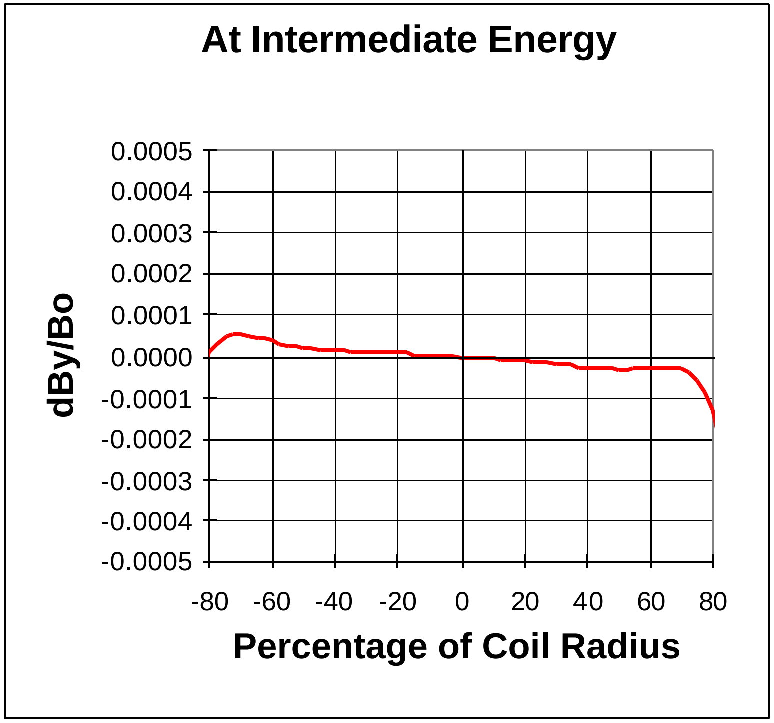
Solutions - build better magnets !

- Persistent currents proportional to Jc x effective filament diameter, hence reduce filament diameter
  - Tevatron 7μ, RHIC 6μ, HERA 16μ, LHC 7μ
  - Filament diameters down to 1μ before Jc degradation, SSC R&D cable at 2.5μ. Issue of cost & yield
- Or reduce Jc
  - Reduces quench performance (hence dynamic range)
- Increase magnet aperture to reduce sensitivity to field harmonics (LHC 50->56mm, SSC 40->50mm)
  - Cost implications

Solutions - build better magnets cont.

- Better inherent field quality: doesn't help much since dynamic effects dominate at low excitation
- Iron dominated magnets: minimal dynamic effects & random harmonics, high field point limited to 2T but magnet dynamic range can be expected to be better (for these magnets other issues dominate related to beam size)
- Higher fields: Nb3Sn effective filament size is 50μ, Jc improves by factor of 7 -> persistent currents increase by ~50 !

RHIC D0 Dipole



Solutions - build better machines !

- Machine Design: Lattice
  - Generally speaking fiscal considerations for large machines cause the arc lattice to be constructed so that field quality is <u>always</u> the low energy issue. In addition large arcs give more optics sensitivity to a unit of magnetic field harmonics (LHC 52:1, RHIC 5:1, chromaticity v dipole b1)
- Machine Design : Parameters
  - Minimise impact of short injection lifetime e.g. rapid cycling injectors, single turn injection
  - Maximise allowable tolerances e.g. 20% beam loss at injection, 100% emittance growth
  - Operate at the highest possible energy e.g. localised temperature control, magnet selection/location
  - Smaller beams reduce aperture demand for fixed beam sigma

Solutions - build better machines ! cont.

- Machine Operations: minimize impact
  - Optimize ramp (everyone does this)
  - Fix cycling criteria e.g. 3 ramps to top energy then dwell (everyone does this)
  - Feed-forward from previous operating cycles (Tev)
  - Feed-back from reference magnets (HERA)
  - Feed-back from online model (LHC)
  - High bandwidth, distributed correction systems (All to some degree)
- Machine Design: innovations
  - Passive correctors
  - Iron dominated magnets at low field
  - HTS ??

Solutions - build better machines ! cont.

- Machine Design: better calculations (allow us to run closer to the 'edge')
  - More computing power
  - More precise field measurements
  - On-line data bases

How well do we really know the input conditions ?

So what's the (correct) dynamic range for a 50 Tev Ring ?

- Very large machines tend to exhibit characteristics that work against a large dynamic range
  - Small apertures, high fields(Nb_3Sn), arc cell length
- Without any innovation then a dynamic range similar to the LHC looks about right. This by itself would require incremental improvements. For 50 Tev then ~3 Tev injection energy (σ = ~0.5mm, ~40 mm coil separation) is reasonable to adopt initially without any other technical information. The high field approach can tolerate emittance dilution and hence a slightly less conservative approach
- If we can make the dynamic effects go away (low-field magnet, technical innovation) and there is sufficient physical aperture then 50:1 dynamic range is not unthinkable (σ = ~ 1 mm)